IJSPT

ORIGINAL RESEARCH

MAXIMAL HIP AND KNEE MUSCLE STRENGTH ARE NOT RELATED TO NEUROMUSCULAR PRE-ACTIVITY DURING SIDECUTTING MANEUVER: A CROSS-SECTIONAL STUDY

Rasmus S. Husted, PT, MSc[1,2]
Jesper Bencke, PhD[1]
Per Hölmich, PhD[3]
Lars L. Andersen, PhD[4,5]
Kristian Thorborg, PhD[3,6,10]
Thomas Bandholm, PhD[2]
Bjørn Gliese, PT, MSc[7]
Hanne B. Lauridsen, MSc[1]
Grethe Myklebust, PT, PhD[8]
Per Aagaard, PhD[9]
Mette K. Zebis, PhD[10]

ABSTRACT

Background: Reduced lower extremity muscle strength as well as reduced lower extremity muscle pre-activity (defined as muscular activity just prior to initial ground contact) during high-risk movements are factors related to increased risk of non-contact ACL injury in adolescent female athletes. A strong relationship exists between muscle strength and muscle activity obtained during an isometric contraction, however, whether these two measures are related when muscle activity is obtained during a movement associated with a high risk of non-contact ACL injury is not known. Absence or presence of such a relationship may have implications for which training modalities to choose in the prevention of ACL injuries.

Purpose*:* The purpose of this study was to examine the relationship between maximal muscle strength of the hip extensors, hip abductors and knee flexors and the pre-activity of these muscle groups recorded during a sidecutting maneuver (high-risk movement) in adolescent female soccer and handball athletes.

Study design*:* Cross-sectional study.

Methods*:* Eighty-five adolescent (age 16.9 ± 1.2 years) female elite handball and soccer athletes were assessed for maximal hip extensor, hip abductor and knee flexor muscle strength; and muscle pre-activity (electromyography recordings over a 10 ms time interval prior to foot ground contact) of the gluteus maximus (Gmax), gluteus medius (Gmed), biceps femoris (BF) and semitendinosus (ST) during a standardized sidecutting maneuver.

Results: The results of the correlation analyses demonstrated poor and statistically non-significant correlations. Maximal hip extensor force (N/kg bw) and Gmax pre-activity [r_s = 0.012 (95% CI -0.202 – 0.224), p = 0.91], maximal hip abductor force (N/kg bw) and Gmed pre-activity [r_s = 0.171 (95% CI -0.044 – 0.371), p = 0.11], maximal knee flexor force (N/kg bw) and BF pre-activity [r_s = 0.049 (95% CI -0.166 – 0.259), p = 0.65], and maximal knee flexor force and ST pre-activity [r_s = 0.085 (95% CI -0.131 – 0.293), p = 0.44].

Conclusion*:* In the present exploratory study, the results imply that no relationship exists between maximal lower extremity isometric muscle strength and lower extremity muscle pre-activity during sidecutting. This means that athletes with low muscle strength may not necessarily demonstrate high (or low) muscle pre-activity during sidecutting - a well-known risk movement for sustaining non-contact ACL injury.

Levels of evidence*:* Level 3

Key words*:* Anterior cruciate ligament, electromyography, muscle strength, neuromuscular activity

[1] Human Movement Analysis Laboratory, Department of Orthopaedic Surgery, Copenhagen University Hospital, Amager-Hvidovre, Hvidovre, Denmark
[2] Optimed, Clinical Research Centre, Copenhagen University Hospital, Amager-Hvidovre, Hvidovre, Denmark
[3] Sports Orthopedic Research Center – Copenhagen (SORC-C), Department of Orthopedic Surgery, Copenhagen University Hospital, Amager-Hvidovre, Hvidovre, Denmark
[4] National Research Centre for the Working Environment, Copenhagen, Denmark
[5] Physical Activity and Human Performance Group, SMI, Department of Health Science and Technology, Aalborg University, Denmark
[6] Physical Medicine & Rehabilitation Research – Copenhagen (PMR-C), Department of Occupational and Physical Therapy, Copenhagen University Hospital, Amager-Hvidovre, Hvidovre, Denmark
[7] Clinical Orthopaedic Research Hvidovre (CORH), Department of Orthopedic Surgery, Copenhagen University Hospital, Amager-Hvidovre, Hvidovre, Denmark
[8] Oslo Sport Trauma Research Center, Norwegian School of Sport Sciences, Oslo, Norway
[9] Department of Sports Sciences and Clinical Biomechanics, SDU Muscle Research Cluster (SMRC), University of Southern Denmark, Odense M, Denmark
[10] Department of Physiotherapy and Occupational Therapy, Faculty of Health and Technology, Metropolitan University College, Copenhagen, Denmark

Authors declare no conflicts of interest.

CORRESPONDING AUTHOR

Mette K. Zebis
Department of Physiotherapy and Occupational Therapy, Faculty of Health and Technology, Metropolitan University College, Copenhagen, Denmark
E-mail: mzeb@phmetropol.dk

DOI: 10.26603/ijspt20180066

INTRODUCTION

The incidence rate (81-85 per 100,000)[1] of non-contact anterior cruciate ligament (ACL) injuries is a major problem in sports. In the prevention of non-contact ACL injuries, the role of lower extremity muscle strength has been discussed extensively[1-4] and research suggests that reduced isolated lower extremity muscle strength is related to an increased risk of non-contact ACL injury in healthy competitive athletes.[5,6]

In a typical non-contact ACL injury situation (sidecutting),[7,8] Bencke and colleagues found that the peak external hip- abduction, inward rotation and extension moments coincided with the peak external knee- valgus and outward rotation moment 30-40 milliseconds (ms) after landing in adolescent female handball players,[9] all of which are factors known to predispose for non-contact ACL injury.[10,11] These finding underline the importance of high dynamic restraint capacity of the hip extensors, hip abductors and knee flexors in the very initial phase of ground contact during sidecutting, in order to counter the stress forces generated in the ACL. To adequately counter these external forces early after foot ground contact during sidecutting, the hip extensors, hip abductors and knee flexors need to be pre-activated in relation to foot ground contact due to the latency of mechanosensory feedback reflexes (>75-100 ms).[12] A potential imbalance between external forces and internal counter-acting muscle force output may partly explain why non-contact ACL injury also is observed in the very initial time window i.e. <40 ms after foot-strike.[8,13] During a high risk ACL injury movement such as sidecutting where numerous lower limb muscles are active at the same time, electromyography (EMG) can be used to measure neuromuscular activity and provide a proxy measure of muscle force output.[14-16] Based on this method, Zebis and colleagues previously reported that the combination of high quadriceps pre-activity along with low medial hamstring pre-activity during sidecutting was a risk factor for sustaining non-contact ACL injury in female athletes.[17]

Reduced muscle strength and reduced muscle pre-activity are both modifiable risk factors for non-contact ACL injury, which can be targeted by specific training interventions.[18-24] Their relationship, however, is currently unknown. As EMG activity provides a proxy measure of muscle force output during movements, the question is if, or how, the two risk factors – i.e. lower extremity muscle strength [5,6] and neuromuscular pre-activity during sidecutting [17] – are related. Three plausible scenarios exist, each with different consequences for the optimal design of injury prevention exercises: 1) High muscle strength down-regulates the amount of pre-activity (less pre-activity is needed to produce the same force output),[18] - or low muscle strength up-regulates the amount pre-activity since more pre-activity is needed to produce the same force output (inverse relationship), implying that the two potential risk factors should be targeted by different training programs; 2) High muscle strength increases neuromuscular coordination by up-regulating pre-activity and thereby increasing the force output (positively related) as seen in static force testing,[25] implying that strength training alone may target both potential risk factors concurrently; 3) No relationship exist between the two potential ACL injury risk factors, which imply that low muscle strength and low muscle pre-activity during high-risk movements should be independently targeted by distinct training programs.

While the hip extensors, hip abductors and knee flexors, also referred to as the posterior kinetic muscle chain, seem important for preventing non-contact ACL injuries,[3] the present study intended to examine if maximal isometric muscle strength in the hip extensors, hip abductors and knee flexors are related to the amount of pre-activity of these muscle groups during a high-risk movement such as the sidecutting manoeuvre.

The purpose of this study was to examine the relationship between maximal muscle strength of the hip extensors, hip abductors and knee flexors and the pre-activity of these muscle groups recorded during a sidecutting maneuver (high-risk movement) in adolescent female soccer and handball athletes.

MATERIALS AND METHODS

Study design and participants

This exploratory study is an embedded part of an ongoing prospective parent cohort study designed to screen Danish adolescent (age range 14-19 years) female soccer and handball athletes for ACL risk factors (unpublished). The reporting of the study follows the STROBE 2007 statement (Strengthening the Reporting of Observational Studies in Epidemiology).[26] Previously, Husted and colleagues reported the association of hamstring and quadriceps pre-activity between different ACL risk screening tests from the same cohort.[27]

Participants were recruited through collaboration with the Danish Soccer Association (DBU) and the Danish Handball Association (DHF). Participants who met the following criteria were included in the study: 1) selected for the national youth team in their respective sports (handball or soccer) and 2) physically fit to participate in a full competitive game or match. Participants were excluded if they were injured at the time of inclusion precluding them from performing the test protocol. Before the test in the motion analysis laboratory, all study participants went through a structured interview to assess number and severity of lower limb injuries sustained in the prior 12 months (anatomical region, cause of injury, type of injury, time away from sport due to injury), total duration of sports participation (playing experience) and on the involvement in systematic resistance training (>2 sessions/week). Data collection took place between November 2010 and December 2011.

Eighty-five adolescent female elite handball (52) and soccer (33) athletes with 10.2 ($\pm$2.5) years of experience with their sport were recruited for the study (age 16.9$\pm$1.2 years; height 172.3$\pm$6.7 cm; weight 66.3$\pm$8.2 kg) (Table 1). All participants and their parents were informed about the purpose and content of the project, and all parents gave written informed consent for their child to participate in the study in accordance with The Declaration of Helsinki. The study was approved by the local Ethics Committee in the Capital Region of Denmark (H-2-2010-091).

Test procedures

Following a structured interview, the following test procedures were performed: 1) measurement of anthropometric data (age, height, weight and determination of dominant leg), 2) EMG-electrode placement on selected muscles, 3) warm-up following a standardized protocol, 4) MVC procedure measuring maximal isometric hip extensor, hip abductor and knee flexor strength and corresponding EMG activity, and 5) the sidecutting test maneuver.

Using procedures described in detail in previous reports[9,18,27] participants were tested in a 3D motion analysis laboratory to assess lower limb muscle activity in selected muscles (Gluteus maximus (Gmax), Gluteus medius (Gmed), long head of the Biceps Femoris (BF) and Semitendinosus (ST)) during a standardized sidecutting maneuver (SC) (additional details given below) using synchronous surface EMG recording. Muscle activity was also recorded during maximal voluntary (isometric) contractions (MVC) for the respective muscles. In brief, maximal isometric hip extensor, hip abductor and knee flexor muscle strength were measured using a handheld dynamometer (details given below). Muscle strength and pre-activity testing was performed on the take-off/stance leg, defined as the leg contralateral to the preferred kicking leg or throwing arm.[19]

EMG recording

Neuromuscular activity was sampled at 1000 Hz using bipolar surface EMG-electrodes with 1.0 cm inter-electrode distance and built-in preamplifiers (Delsys DE-2.3 sEMG sensor; CMRR >80 dB).[18,27] The skin was shaved to remove hair and dead skin cells and cleaned with ethanol to ensure minimal skin impedance.[25] Subsequently, the EMG-electrodes were placed along the length of the fibers of the Gmax, Gmed, BF and ST muscles. To reduce noise contamination from external electric sources a reference electrode was placed on the anterior tibial crest.[25] To ensure reliable EMG-electrode placement between days and testers the guidelines described by Perotto et al. were used.[28] Bipolar EMG-recordings from lower extremity muscles during both isometric muscle contractions and ballistic movements have previously been found reliable.[19,29]

Table 1. *Participant characteristics (n = 85).*

	Age (yrs)	Height (cm)	Weight (kg)	Sport (handball: soccer)	Experience with sport (yrs)	Performing resistance training >2 sessions/week
Mean (SD)	16.9 (1.2)	172.3 (6.7)	66.3 (8.2)	52:33	10.2 (2.5)	Yes = 81, No = 4

Warm-up procedure

Before measuring maximal voluntary contraction strength all participants went through a standardized warm-up procedure consisting of ten submaximal vertical jumps, ten one-leg squats on each leg, ten medium vertical jumps (80% self-rated effort), ten lunges on each leg and finally ten maximal vertical countermovement jumps (100% self-rated effort).

Maximum voluntary contraction (MVC)

Maximal voluntary isometric muscle strength was measured using a portable hand-held dynamometer (PowerTrack II Commander, JTECH Medical, Salt Lake City, Utah, USA) according to procedures described elsewhere.[30-32] In each trial the participants had four seconds to reach maximum isometric force production (i.e. hip extension, hip abduction and knee flexion). The participants performed three MVC trials for each muscle group separated by 30 seconds of rest to avoid fatigue, receiving strong verbal encouragement. The trial with highest (maximum) isometric force production for each muscle group was selected for later analysis.[30] Maximal hip extensor, hip abductor and knee flexor muscle forces were normalized to body weight (N/kg bw).

<u>Knee flexor muscle force:</u> Maximal isometric knee flexor force was obtained with the participant lying prone on an examination table, the foot and ankle free of the edge of the couch, the knee in 10° flexion, a handheld dynamometer placed 5 cm proximal from the medial malleolus, a strap (attached to the floor) wrapped around the ankle and the dynamometer and then performing a maximal isometric knee flexion (Figure 1 A).[31,32] Prior to each MVC trial it was ensured that the dynamometer was not registering any tension and that the leg was held closely against the strap to avoid any initial acceleration impact against the dynamometer.

Figure 1. *Muscle force (N) was measured with a handheld dynamometer and muscle activity was measured using bipolar surface EMG recording.* ***A.*** *Maximal isometric knee flexor force,* ***B.*** *Maximal isometric hip abductor force,* ***C.*** *Maximal isometric hip extensor force,* ***D.*** *Side cutting maneuver in the 3D motion analysis laboratory. The left foot is placed on the force plate.*

Hip abductor muscle force: Maximal hip abductor force was obtained with the participant supine on the examination couch, the test leg lifted 1 cm above the surface of the couch and 20° of hip abduction. In this position the dynamometer was positioned against the lateral side of the lower leg 5 cm proximal from the medial malleolus and a maximal isometric hip abduction trial was performed against the researcher (Figure 1 B).[30,31]

Hip extensor muscle force: Maximal hip extensor force was obtained using a set-up similar to that of knee flexor MVC testing except that the knee joint was fully extended and the instruction was to maximally extend the hip and not flex the knee (Figure 1 C).[30,31]

Sidecutting (SC)

As described in detail previously [18,27] the participants started five meters in front of an instrumented force plate and were instructed to perform the SC maneuver as fast and powerfully as possible to simulate an in-game situation (Figure 1 D). To best simulate a match situation neither cutting angle nor run-in speed was standardized. To ensure that the participants were able to move freely during the SC test all the EMG-electrodes were connected to a wireless transmitter placed on the participants back. The test was repeated until three approved SC trials were captured. The mean of the recorded EMG-signal amplitudes from the three approved SC trials was calculated for each muscle, respectively, for later analysis.[18,27]

EMG signal processing

For each muscle (Gmax, Gmed, BF and ST) all EMG recordings were high-pass filtered using 4th order zero-lag Butterworth filter and subsequently smoothened using a root-mean-squared (RMS) filter (30-ms symmetrical moving window with successive 1-ms steps). EMG-signal amplitudes recorded from the three SC trials of each participant were normalized to the maximum RMS EMG amplitude recorded during MVC testing of the respective muscles (i.e. hip extensor, hip abductor and knee flexor). Neuromuscular pre-activity during the SC maneuver thus refers to the mean normalized RMS EMG amplitude measured in the 10-ms time interval immediately preceding initial foot contact (time = 0) (Figure 2).[17,18,27] Details of the EMG signal processing procedure have been described in detail elsewhere.[27]

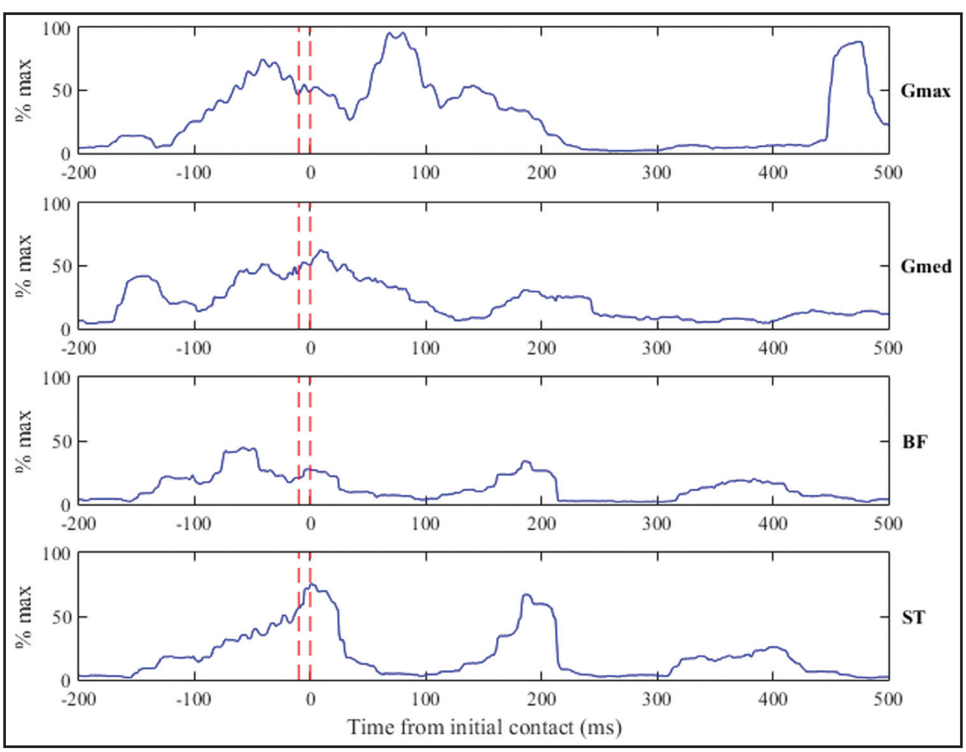


Figure 2. *The mean RMS EMG amplitude during the 10-ms time interval prior to initial contact (dotted red lines) was calculated for the Gmax, Gmed, BF and ST muscles and normalized to the peak EMG amplitude obtained during MVC of the respective muscles examined.*

Table 2. *Characteristics of maximal isometric hip extensor, hip abductor and knee flexor force output, normalized to body weight maximal isometric hip extensor, hip abductor and knee flexor force output (N/kg bw) and Gmax, Gmed, BF and ST pre-activity.*

n = 85	Median	10^{th} – 90^{th} percentiles
Maximal hip extensor force (N)	246	200 - 289
Maximal hip abductor force (N)	169	140 - 206
Maximal knee flexor force (N)	261	222 - 308
Maximal hip extensor force normalized to body weight (N/kg bw)	3.8	2.9 – 4.3
Maximal hip abductor force normalized to body weight (N/kg bw)	2.5	2.2 - 2.9
Maximal knee flexor force normalized to body weight (N/kg bw)	4.0	3.4 - 4.7
Gmax pre-activity (% MVC)*	41%	14 - 74%
Gmed pre-activity (% MVC)†	66%	33 - 108%
BF pre-activity (% MVC)‡	30%	12 - 46%
ST pre-activity (% MVC)‡	41%	22 - 77%

N = Newton, N/kg bw = Newton per kilograms of body weight, Gmax = gluteus maximus, Gmed = gluteus medius, BF = biceps femoris, ST = semitendinosus, MVC = maximal voluntary (isometric) contraction. Percent of maximal EMG activity measured during sidecutting and normalized to maximal isometric hip extensor*, hip abductor† and knee flexor‡ contraction EMG activity. Median and 10^{th} – 90^{th} percentiles.

Table 3. *Correlation analyses of the maximal isometric hip extensor, hip abductor and knee flexor muscle force (N/kg bw) versus Gmax, Gmed, BF and ST muscle pre-activity.*

	r	95% CI	p-value
Gmax pre-activity vs. Hip extensor force (N/kg bw)*	0.012	-0.202 – 0.224	0.91
Gmed pre-activity vs. Hip abductor force (N/kg bw)*	0.171	-0.044 – 0.371	0.11
BF pre-activity vs. Knee flexor force (N/kg bw)*	0.049	-0.166 – 0.259	0.65
ST pre-activity vs. Knee flexor force (N/kg bw)*	0.085	-0.131 – 0.293	0.44

N/kg bw = Newton per kilograms of body weight, Gmax = gluteus maximus, Gmed = gluteus medius, BF = biceps femoris, ST = semitendinosus. *Spearman Rank Correlation test.

Statistical analysis

The Shapiro Wilk test was used to test for normal distribution of all obtained data. The EMG data were not normally distributed; consequently, it was decided to use non-parametric statistics and to present data as medians with corresponding 10^{th}-90^{th} percentile ranges. Accordingly the non-parametric Spearman's Rho Correlation test (r_s) was used to test the relationship between the maximal isometric hip extensor, hip abductor and knee flexor muscle force (N/kg bw) versus Gmax, Gmed, BF and ST muscle pre-activity. The following values were used to characterize the strength of correlation, 0.00-0.25 (no or poor relationship), 0.25-0.50 (low-to-moderate relationship), 0.50-0.75 (moderate-to-strong relationship) and above 0.75 (strong-to-excellent relationship).[33] Level of significance was set at 0.05 (two-tailed testing). All statistical analyses were performed using Stata 11.2. No sample size estimation was conducted due to the explorative design of the study.

RESULTS

Maximal isometric hip extensor, hip abductor and knee flexor force output in absolute (N), body mass normalized to terms (N/kg bw) and Gmax, Gmed, BF and ST pre-activity recorded during the sidecutting maneuver, are presented in Table 2.

The results of the correlation analyses demonstrated poor and statistically non-significant correlations. Maximal hip extensor force (N/kg bw) and Gmax pre-activity [r_s = 0.012 (95% CI -0.202 – 0.224), p = 0.91], maximal hip abductor force (N/kg bw) and Gmed pre-activity [r_s = 0.171 (95% CI -0.044 – 0.371), p = 0.11], maximal knee flexor force (N/kg bw) and BF pre-activity [r_s = 0.049 (95% CI -0.166 – 0.259), p = 0.65], and maximal knee flexor force and ST pre-activity [r_s = 0.085 (95% CI -0.131 – 0.293), p = 0.44] (Table 3).

DISCUSSION

The results of the present study did not identify any systematic relationship between the maximal isometric muscle strength of the hip extensors, hip abductors and knee flexors and the pre-activity of these muscles recorded during a standardized sidecutting maneuver.

The cause of non-contact ACL injury is considered to be multifactorial with both lower extremity muscle strength and muscle pre-activity suggested as contributing factors.[2,5,6,17] Interestingly, the results of the present study show no relationship between these two factors (muscle strength and pre-activity); suggesting that high muscle strength not necessarily is accompanied by high muscle pre-activity during standardized sidecutting maneuver or vice versa in adolescent female handball and soccer elite athletes.

With regard to the prevention of ACL injuries, recent systematic reviews have suggested that neuromuscular training (NMT) is effective for preventing lower limb injuries, i.e. reducing the incidence of non-contact ACL injuries.[34-36] The concept of NMT involves multiple exercise options including muscle strengthening, balance/coordination, plyometric, and core exercises, altogether aiming at increasing muscle strength, improving postural balance control and muscle coordination during high-risk movement conditions related to non-contact ACL injury.[34-36]

Interestingly, in a recent study Moeller and colleagues found that strength training was reported to be carried out more often in weekly training than 'balance training' and/or 'specific jump training' (i.e. 2-5 times a week vs. 1-2 times a week, respectively) among adolescent and senior elite handball players.[37] The adolescent athletes examined in the present study are highly comparable to the athletes recruited by Moller and colleagues in terms of gender, age, type of sport, experience with their sport and time spent on resistance training (Table 1). While it is well established that strength training increases muscle strength via both increased neural drive to the muscles and gains in muscle cross-sectional area,[21,23,24] the present data indicate no relationship between maximal muscle strength and the pattern of pre-landing neuromuscular motor activity during a sidecutting maneuver. Speculatively, this suggests that, strength gains from e.g. resistance training may not necessarily result in adopting a certain type of pre-activity motor pattern, probably unless combined with other NMT modalities. Conversely, significant motor pattern re-modelling has been suggested to occur in response to NMT involving balance/coordination exercises, specific jump training and strength training.[18-20]

Although recent meta-analyses emphasize the importance of including all types of NMT modalities in the prevention of non-contact ACL injuries,[38,39] a possible explanation why resistance training may be prioritized higher than the other modalities of the NMT concept could be that besides increasing muscle strength, resistance training is also documented to improve athletic performance ability e.g. making subjects jump higher or run faster.[40,41] Interestingly, in this context, studies have found that plyometric exercises [42] and balance/coordination exercises [19,43] have shown similar improvements in functional performance (e.g. comparable gains in maximal vertical jump height), suggesting some transfer effect from these other exercises modalities of the NMT concept onto athletic performance gains.

To describe the distribution of athletes with high or low muscle force and high or low muscle pre-activity during the standardized side-cutting manoeuvre a subsequent analysis was performed by dividing the plots from the correlation analyses into four median frames (A: low muscle force and high muscle pre-activity, B: high muscle force and high muscle pre-activity, C: low muscle force and low muscle pre-activity, D: high muscle force and low muscle pre-activity), e.g. maximal knee flexor force normalized to body weight and normalized ST pre-activity (Figure 3, Figures for remaining muscles can be found in supplementary online material). This distribution divided the athletes into four subgroups for analysis. This supplemental analysis shows a similar distribution of participants in the four median subgroups (A-D) for all investigated muscles (Table 4). Thus, there appear to be no tendency towards athletes clustering more in one median subgroup compared to the others. However, this analysis highlights one particular subgroup (Figure 3 C), namely athletes with both low muscle force and low muscle pre-activity representing a high total sum of risk factors.[5,6,17] Thus, based on previous observations, the present study participants identified in median subgroup C may be expected to be at higher risk

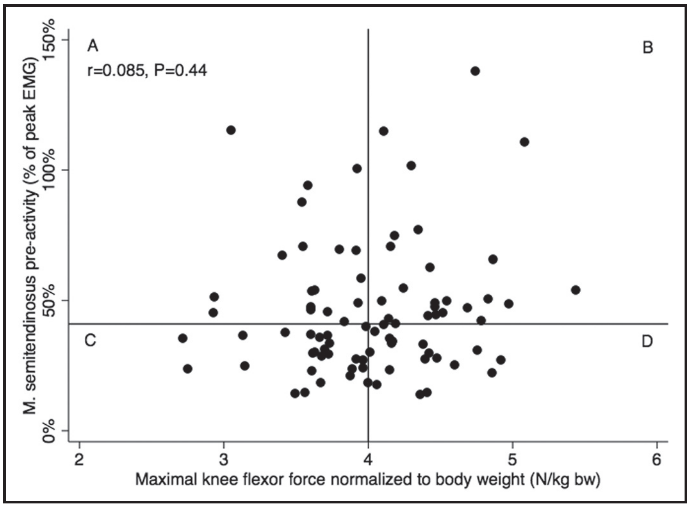


Figure 3. *Scatterplot of correlation between maximum knee flexor force normalized to body weight (N/kg bw) and semitendinosus pre-activity with median lines dividing the scatterplot into four frames; A = Low muscle force, High muscle pre-activity. B = High muscle force, High muscle pre-activity. C = Low muscle force, Low muscle pre-activity. D = High muscle force, Low muscle pre-activity.*

of sustaining non-contact ACL injury compared to their fellow athletes (especially athletes in subgroup B: high muscle force and high muscle pre-activity) as they are found to have both risk factors (low muscle force and low muscle pre-activity), underlining the importance of initiating specialized and targeted NMT among this specific subpopulation of presumed high-risk athletes.

Not only the present observations (no relationship exists between maximal lower extremity isometric muscle strength and lower extremity muscle pre-activity during sidecutting) but also the fact that plyometric and balance/coordination exercises seem poorly integrated in daily training among adolescent female athletes [37] seems alarming bearing in mind the high risk of non-contact ACL injury in this particular population.[1,44-47] Future preventive efforts should focus on implementing *all* types of NMT in the daily training routines, i.e. exercise programs featuring training drills that target muscle strength, plyometric, balance/coordination, and core exercises.

LIMITATIONS

The present study participants were not asked to which extent they performed various sub-types (balance/coordination, plyometric and core exercise) of NMT exercises. However, the participants in the present study were highly comparable to those recruited by Moller and coworkers in regard to age, gender, sport, level of competition and resistance training background.[37]

There are some limitations to the MVC assessments. Isometric MVC assessments cannot provide specific information on individual muscle force contributions. Assessing muscle force with a handheld dynamometer provides the muscle force produced in the assessed movement direction not the muscle force produced by specific muscles. E.g. when assessing hip abductor force, the prime mover is the gluteus medius, however, other hip abductor muscles contribute as well. When assessing hip extensor force, contralateral hip flexor activation may have added to the force output. This could overestimate the recorded muscle force output. Also, isometric MCV assessments may not be representative of muscle activity during dynamic muscle actions.

Because only isometric muscle force was measured, a limitation to the current study is the lack of data on the rate of force development (RFD) during the respective muscle contractions. This could potentially have provided an important input to

Table 4. *Supplemental analysis.*

Athlete distribution in four median subgroups	A	B	C	D
Gmax pre-activity and hip extensor force median, n (%)	20 (23.5)	24 (28.2)	23 (27.1)	18 (21.2)
Gmed pre-activity and hip abductor force median, n (%)	16 (18.8)	26 (30.5)	22 (25.9)	21 (24.8)
BF pre-activity and knee flexor force median, n (%)	23 (27.1)	19 (22.3)	20 (23.5)	23 (27.1)
ST pre-activity and knee flexor force median, n (%)	18 (21.2)	23 (27.1)	24 (28.2)	20 (23.5)

Gmax = gluteus maximus, Gmed = gluteus medius, BF = biceps femoris, ST = semitendinosus. Total n = 85. A = Low muscle force, High muscle pre-activity. B = High muscle force, High muscle pre-activity. C = Low muscle force, Low muscle pre-activity. D = High muscle force, Low muscle pre-activity. Median subgroups were determined by the median value of the two variables in the correlation analysis (isometric muscle strength and muscle pre-activity).

the present analysis, as RFD assessment previously have added further perspective on the aspect of non-contact ACL injury in female soccer athletes.[48]

CONCLUSIONS

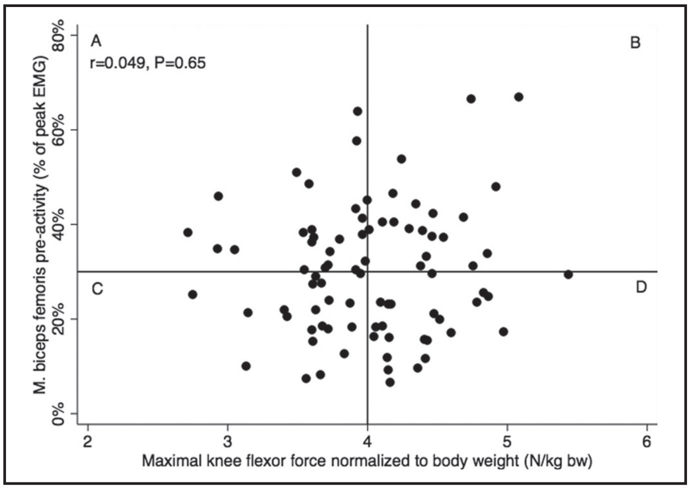
In the present exploratory study, the results imply that no relationship exists between maximal lower extremity isometric muscle strength and lower extremity muscle pre-activity during sidecutting. This means that athletes with low muscle strength may not necessarily demonstrate high (or low) muscle pre-activity during sidecutting - a well-known risk movement for sustaining non-contact ACL injury.

REFERENCES

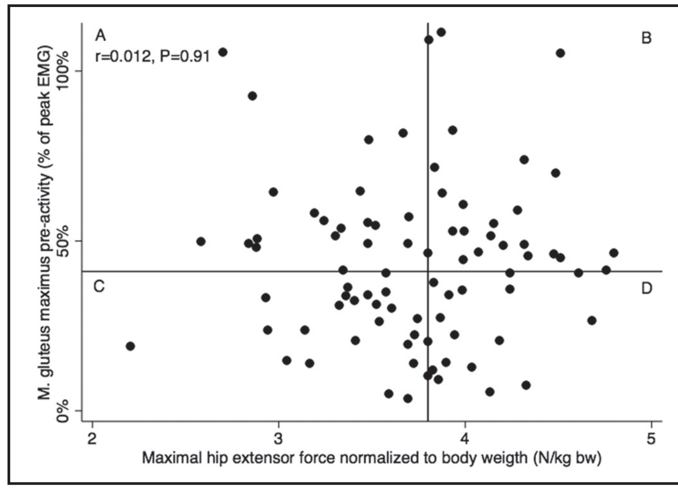
1. Renstrom P, Ljungqvist A, Arendt E, et al. Non-contact ACL injuries in female athletes: an International Olympic Committee current concepts statement. *Br J Sports Med.* 2008;42(6):394-412.
2. Bien DP. Rationale and implementation of anterior cruciate ligament injury prevention warm-up programs in female athletes. *J Strength Cond Res.* 2011;25(1):271-285.
3. Hewett TE, Ford KR, Hoogenboom BJ, Myer GD. Understanding and preventing ACL injuries: current biomechanical and epidemiologic considerations - update 2010. *N Am J Sports Phys Ther.* 2010;5(4):234-251.
4. Hewett TE, Myer GD, Ford KR, Paterno MV, Quatman CE. The 2012 ABJS Nicolas Andry Award: The sequence of prevention: a systematic approach to prevent anterior cruciate ligament injury. *Clin Orthop Rel Res.* 2012;470(10):2930-2940.
5. Khayambashi K, Ghoddosi N, Straub RK, Powers CM. Hip muscle strength predicts noncontact anterior cruciate ligament Injury in male and female athletes: A prospective study. *Am J Sports Med.* 2016;44(2):355-361.
6. Myer GD, Ford KR, Barber Foss KD, Liu C, Nick TG, Hewett TE. The relationship of hamstrings and quadriceps strength to anterior cruciate ligament injury in female athletes. *Clin J Sport Med.* 2009;19(1):3-8.
7. Olsen OE, Myklebust G, Engebretsen L, Bahr R. Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. *Am J Sports Med.* 2004;32(4):1002-1012.
8. Koga H, Nakamae A, Shima Y, et al. Mechanisms for noncontact anterior cruciate ligament injuries: knee joint kinematics in 10 injury situations from female team handball and basketball. *Am J Sports Med.* 2010;38(11):2218-2225.
9. Bencke J, Curtis D, Krogshede C, Jensen LK, Bandholm T, Zebis MK. Biomechanical evaluation of the side-cutting manoeuvre associated with ACL injury in young female handball players. *Knee Surg Sports Traumatol Arthrosc.* 2012.
10. McLean SG, Huang X, van den Bogert AJ. Association between lower extremity posture at contact and peak knee valgus moment during sidestepping: implications for ACL injury. *Clin Biomech.* 2005;20(8):863-870.
11. McLean SG, Huang X, van den Bogert AJ. Investigating isolated neuromuscular control contributions to non-contact anterior cruciate ligament injury risk via computer simulation methods. *Clin Biomech.* 2008;23(7):926-936.
12. Dyhre-Poulsen P, Krogsgaard MR. Muscular reflexes elicited by electrical stimulation of the anterior cruciate ligament in humans. *J Appl Physiol.* 2000;89(6):2191-2195.
13. Krosshaug T, Nakamae A, Boden BP, et al. Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. *Am J Sports Med.* 2007;35(3):359-367.
14. Hof AL. The relationship between electromyogram and muscle force. *Sportverletz Sportschaden.* 1997;11(3):79-86.
15. Aagaard P, Simonsen EB, Andersen JL, Magnusson SP, Bojsen-Moller F, Dyhre-Poulsen P. Antagonist muscle coactivation during isokinetic knee extension. *Scand J Med Sci Sports.* 2000;10(2):58-67.
16. Alkjaer T, Simonsen EB, Magnusson SP, Dyhre-Poulsen P, Aagaard P. Antagonist muscle moment is increased in ACL deficient subjects during maximal dynamic knee extension. *Knee.* 2012;19(5):633-639.
17. Zebis MK, Andersen LL, Bencke J, Kjaer M, Aagaard P. Identification of athletes at future risk of anterior cruciate ligament ruptures by neuromuscular screening. *Am J Sports Med.* 2009;37(10):1967-1973.
18. Zebis MK, Andersen LL, Brandt M, et al. Effects of evidence-based prevention training on neuromuscular and biomechanical risk factors for ACL injury in adolescent female athletes: a randomised controlled trial. *Br J Sports Med.* 2016;50(9):552-557.
19. Zebis MK, Bencke J, Andersen LL, et al. The effects of neuromuscular training on knee joint motor control during sidecutting in female elite soccer and handball players. *Clin J Sport Med.* 2008;18(4):329-337.
20. Wilderman DR, Ross SE, Padua DA. Thigh muscle activity, knee motion, and impact force during side-step pivoting in agility-trained female basketball players. *J Athl Train.* 2009;44(1):14-25.

21. Gabriel DA, Kamen G, Frost G. Neural adaptations to resistive exercise: mechanisms and recommendations for training practices. *Sports Med.* 2006;36(2):133-149.
22. Aagaard P. Training-induced changes in neural function. *Exerc Sport Sci Rev.* 2003;31(2):61-67.
23. Aagaard P, Andersen JL, Dyhre-Poulsen P, et al. A mechanism for increased contractile strength of human pennate muscle in response to strength training: changes in muscle architecture. *J Physiol.* 2001;534(Pt. 2):613-623.
24. Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P. Increased rate of force development and neural drive of human skeletal muscle following resistance training. *J Appl Physiol.* 2002;93(4):1318-1326.
25. Konrad P. *The ABC of EMG – a practical introduction to kinesiological electromyography.* Version 1.0, April.: Noraxon Inc, USA.; 2005.
26. Vandenbroucke JP, von Elm E, Altman DG, et al. Strengthening the reporting of observational studies in epidemiology (STROBE): Explanation and elaboration. *Int J Surg.* 2014.
27. Husted RS, Bencke J, Andersen LL, et al. A comparison of hamstring muscle activity during different screening tests for non-contact ACL injury. *Knee.* 2016.
28. Perotto AO, Delagi, E. F., Iazetti, J., & Morrison, D. *Anatomical Guide For The Electromyographer – The Limbs And Trunk.*: Sringfield. Illinois. U.S.A.: Charles C Thomas; 2005.
29. Fauth ML, Petushek EJ, Feldmann CR, et al. Reliability of surface electromyography during maximal voluntary isometric contractions, jump landings, and cutting. *J Strength Cond Res* 2010;24(4):1131-1137.
30. Thorborg K, Bandholm T, Holmich P. Hip- and knee-strength assessments using a hand-held dynamometer with external belt-fixation are inter-tester reliable. *Knee Surg Sports Traumatol Arthrosc.* 2013;21(3):550-555.
31. Thorborg K, Petersen J, Magnusson SP, Holmich P. Clinical assessment of hip strength using a hand-held dynamometer is reliable. *Scand J Med Sci Sports.* 2010;20(3):493-501.
32. Askling C, Saartok T, Thorstensson A. Type of acute hamstring strain affects flexibility, strength, and time to return to pre-injury level. *Br J Sports Med.* 2006;40(1):40-44.
33. Portney LG, Watkins MP. *Foundations of Clinical Research: applications to practice.* 3rd ed. Upper Saddle River, N.J.: Pearson Prentice Hall; 2009.
34. Myer GD, Sugimoto D, Thomas S, Hewett TE. The influence of age on the effectiveness of neuromuscular training to reduce anterior cruciate ligament injury in female athletes: a meta-analysis. *Am J Sports Med.* 2013;41(1):203-215.
35. Gagnier JJ, Morgenstern H, Chess L. Interventions designed to prevent anterior cruciate ligament injuries in adolescents and adults: a systematic review and meta-analysis. *Am J Sports Med.* 2013.
36. Sadoghi P, von Keudell A, Vavken P. Effectiveness of anterior cruciate ligament injury prevention training programs. *J Bone Joint Sugr Am.* 2012;94(9):769-776.
37. Moller M, Attermann J, Myklebust G, Wedderkopp N. Injury risk in Danish youth and senior elite handball using a new SMS text messages approach. *Br J Sports Med.* 2012;46(7):531-537.
38. Sugimoto D, Myer GD, Barber Foss KD, Pepin MJ, Micheli LJ, Hewett TE. Critical components of neuromuscular training to reduce ACL injury risk in female athletes: meta-regression analysis. *Br J Sports Med.* 2016.
39. Sugimoto D, Alentorn-Geli E, Mendiguchia J, Samuelsson K, Karlsson J, Myer GD. Biomechanical and neuromuscular characteristics of male athletes: implications for the development of anterior cruciate ligament injury prevention programs. *Sports Med.* 2015;45(6):809-822.
40. Harries SK, Lubans DR, Callister R. Resistance training to improve power and sports performance in adolescent athletes: a systematic review and meta-analysis. *J Sci Med Sport.* 2012;15(6):532-540.
41. Sperlich PF, Behringer M, Mester J. The effects of resistance training interventions on vertical jump performance in basketball players: a meta-analysis. *J Sports Med Phys Fitness.* 2015.
42. Hewett TE, Stroupe AL, Nance TA, Noyes FR. Plyometric training in female athletes. Decreased impact forces and increased hamstring torques. *Am J Sports Med.* 1996;24(6):765-773.
43. Holm I, Fosdahl MA, Friis A, Risberg MA, Myklebust G, Steen H. Effect of neuromuscular training on proprioception, balance, muscle strength, and lower limb function in female team handball players. *Clin J Sport Med.* 2004;14(2):88-94.
44. Waldén M, Hagglund M, Werner J, Ekstrand J. The epidemiology of anterior cruciate ligament injury in football (soccer): a review of the literature from a gender-related perspective. *Knee Surg Sports Traumatol Arthrosc.* 2011;19(1):3-10.
45. Myklebust G, Maehlum S, Engebretsen L, Strand T, Solheim E. Registration of cruciate ligament injuries in Norwegian top level team handball. A prospective study covering two seasons. *Scand J Med Sci Sports.* 1997;7(5):289-292.
46. Bjordal JM, Arnly F, Hannestad B, Strand T. Epidemiology of anterior cruciate ligament injuries in soccer. *Am J Sports Med.* 1997;25(3):341-345.
47. Lind M, Menhert, F., Pedersen AB. Incidence and outcome after revision anterior cruciate ligament reconstruction: results from the Danish registry for knee ligament reconstructions. *Am J Sports Med.* 2012;40(7):1551-1557.
48. Zebis MK, Andersen LL, Ellingsgaard H, Aagaard P. Rapid hamstring/quadriceps force capacity in male vs. female elite soccer players. *J Strength Cond Res.* 2011;25(7):1989-1993.

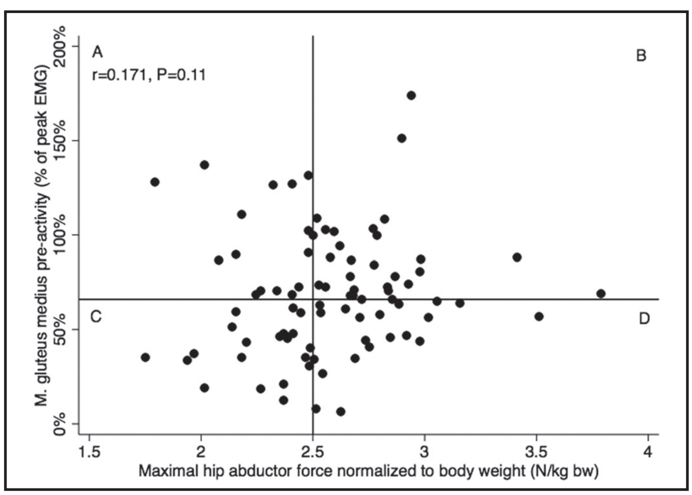
SUPPLEMENTARY FILE



Supplementary File 1. *Scatterplot of correlation between maximum knee flexor force normalized to body weight (N/kg bw) and m. biceps femoris pre-activity with median lines dividing the scatterplot into four frames; A = Low muscle force, High muscle pre-activity. B = High muscle force, High muscle pre-activity. C = Low muscle force, Low muscle pre-activity. D = High muscle force, Low muscle pre-activity.*



Supplementary File 2. *Scatterplot of correlation between maximum hip extensor force normalized to body weight (N/kg bw) and m. gluteus maximus pre-activity with median lines dividing the scatterplot into four frames; A = Low muscle force, High muscle pre-activity. B = High muscle force, High muscle pre-activity. C = Low muscle force, Low muscle pre-activity. D = High muscle force, Low muscle pre-activity.*



Supplementary File 3. *Scatterplot of correlation between maximum hip abductor force normalized to body weight (N/kg bw) and m. gluteus medius pre-activity with median lines dividing the scatterplot into four frames; A = Low muscle force, High muscle pre-activity. B = High muscle force, High muscle pre-activity. C = Low muscle force, Low muscle pre-activity. D = High muscle force, Low muscle pre-activity.*